Lasers in Surgery and Medicine 22:86–96 (1998)

Feedback Interstitial Diode Laser (805 nm) Thermotherapy System: Ex Vivo Evaluation and Mathematical Modeling With One and Four-Fibers

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Background and Objective: **In this study a newly developed microprocessor controlled power regulation and thermometry system integrated with a diode laser (805 nm wavelength) was evaluated with respect to temperature distribution, effectiveness of regulation, and ability to predict temperature distributions by computer simulation.**
Study Design/Materials and Methods: **Experiments were performed in ground bovine muscle using either a single laser fiber or four-fibers. The target temperature at one (feedback) thermistor, placed 5 mm from one of the laser fibers, was set to 50°C and was maintained by means of stepwise power regulation. The temperature distribution was monitored using multiple thermistor probes. A numerical model based on the bioheat equation was used to calculate the temperature distributions.**
Results: **Temperature regulation was excellent with a tendency towards better regulation in the four-fiber than in the single-fiber experiments. Agreement between calculated and measured temperatures was good. The coagulated (>55°C) and hyperthermic (>45°C) volumes were 6 and 10–11 times larger, respectively, with four-fibers than with a single fiber.**
Conclusion: **It is concluded that the stepwise power regulation system was efficient in maintaining a stable target temperature. The results indicate that the system can produce lesion volumes adequate for treating a relatively large tumor in a single session and that computer simulation may be useful for predicting temperature distribution. Lasers Surg. Med. 22:86–96, 1998.**
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Key words: **coagulated volume; hyperthermia; regulation; sapphire probe; temperature distribution**

Contract grant sponsor: Swedish Cancer Society; Contract grant numbers: 3163-B95-03XAA, 95-1161; Contract grant sponsor: Swedish Medical Research Council; Contract grant number: B95-17X-07183; Contract grant sponsor: Crafoord Foundation; Contract grant sponsor: Lund University; Contract grant sponsor: Gunnar Arvid and Elisabeth Nilsson's Foundation for Cancer Treatment; Contract grant sponsor: Mrs. Berta Kamprad's Foundation for Cancer Treatment; Contract grant sponsor: Lund Health Care District's Research Foundations; Contract grant sponsor: Royal Physiographic Society in Lund; Contract grant sponsor: John and Augusta Persson's Foundation for Scientific Medical Research; Contract grant sponsor: Bergþóra Magnúsdóttir and Jakob J. Bjarnason Memorial Foundation.

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Accepted 9 September 1997

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INTRODUCTION

Interstitial thermotherapy denotes the elevation of temperature at local spots within tissues to a level where cell death is enabled. In interstitial laser thermotherapy (ILT), heat is delivered to tissues through the absorption of light, and the rise in temperature results in a well-defined region of necrosis [1]. The size of the coagulated lesion depends on several parameters, such as the wavelength of the laser light, output power, time of exposure, and optical and thermal properties of the tissues [2]. Furthermore, blood flow affects temperature distribution and lesion size [3,4]. In order to obtain improved control, a temperature sensor has been used by some to provide feedback for regulation of the delivered energy, accomplished by switching the laser on or off [5,6]. The sensor can be positioned at a strategical point, e.g., at the border of the tumor, and the temperature kept constant at that position through computer controlled feedback regulation of the laser output.

In surgical applications the Nd:YAG laser (1,064 nm wavelength) has been the most widely used laser because of its general availability and because near infrared light penetrates tissue deeper than other common laser light wavelengths [7]. The diode laser has recently emerged as an alternative to the Nd:YAG laser [8]. It has also been applied in interstitial laser thermotherapy [9–11] but has, to our knowledge, not been used in systems with feedback control.

In this work we used a newly developed microprocessor controlled power regulation and thermometry system integrated with a diode laser (805 nm wavelength). Experiments were performed in ground bovine muscle, by using a single-fiber and a four-fiber setup, in order to evaluate the ILT system for future clinical use. The temperature was controlled at one feedback thermistor through stepwise changes in output power. Regulation with the feedback thermistor positioned at 5 mm distance from the fiber tip was examined. The temperature distribution was monitored by several thermistor probes. A numerical model based on the bioheat equation and Monte Carlo calculations of the optical absorption pattern was used to theoretically estimate the overall temperature distribution, which was then compared with measured data. Coagulated and hyperthermic volumes were calculated from the model. Evaluation was done with respect to temperature distribution, effectiveness of regulation and ability to predict temperature distributions by computer simulation.

MATERIALS AND METHODS

ILT System

The thermotherapy system consists of a diode laser unit, with fibers and sapphire probes, and a combined thermometry and power regulation unit (control unit) interfaced with the laser, as illustrated in Figure 1.

Diode laser. The 805 nm light was produced by a GaAlAs diode laser (Diomed 25, Diomed, Cambridge, UK). The output power can be varied between 0.5 and 25 W, with an inherent stability of 2%, and the laser can be remotely controlled. The small dimensions (15 × 38 × 41 cm) and the possibility to use an ordinary 100–240 VAC power supply makes the laser convenient to use.

A 23 mm long and 2 mm maximum diameter artificial sapphire probe with a 5 mm frosted region at its end (ERP10, SLT, Malvern, PA) was used to deliver light interstitially. The sapphire probe was connected to a 600 μm diameter fiber, housed in a polyvinyl sheath (DM-6070, Diomed, Cambridge, UK). The metal connector on the sapphire probe was sealed with thin, heat-resistant polyvinylidenefluoride (PVDF) tubing (Alpha Wire Co., Elizabeth, NJ) to prevent entry of tissue through the air/fluid outlet and direct contact of the metal with tissue.

An optical beam splitter (Diomed, Cambridge, UK) was used in the four-fiber experiments. Transmission measurements using an integrating sphere power meter (Mod. 2015, Laser Therapeutics, Inc., Buellton, CA) showed that the transmission loss at the fiber/sapphire-probe connector was 33% of the light reaching the connector and that there was almost no energy loss in the fiber distributor. The transmitted light through the distributor was somewhat unevenly distributed among the exit ports. With 100% taken as the norm, the output power from the four exit ports was 95%, 117%, 103%, and 85%, respectively.

Thermometry system. The Digital Thermometry System (DTS, Microtherm AB, Lund, Sweden) consists of a control unit and a connector box for the thermistor probes. Temperature is measured with thermistors embedded within probes. The probes consist of medical grade teflon (outer diameter: 0.5 mm) inserted into a steel can-

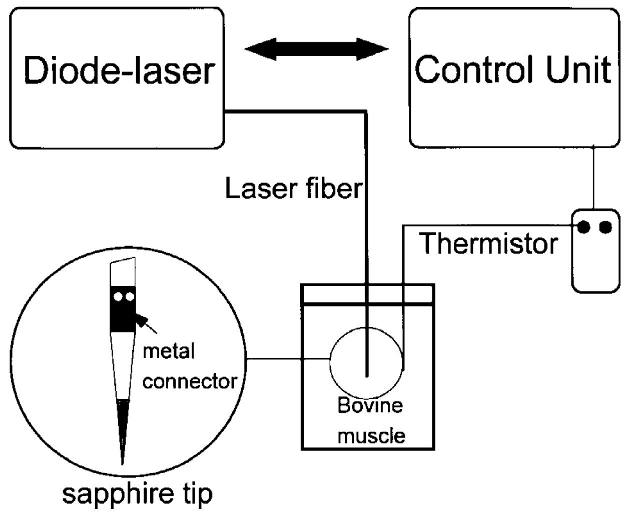

Fig. 1. Schematic illustration of the ILT system. The system consists mainly of a diode laser and a control unit for temperature monitoring and power regulation. A maximum of 14 thermistors (two five-sensor probes and four single-sensor probes) can be connected to a small box providing input to the control unit.

nula (outer diameter: 0.8 mm) for direct puncture. The thermistors are placed inside the teflon sheath which is sealed at its distal end. When the probe contains more than one thermistor, slots in the steel housing are present where they are located. The thermistors give a fast response (< 1 s), and temperatures are monitored with an accuracy of < 0.2°C. All thermistors provide input to the control unit, which contains a microprocessor with additional circuitry for communication with the laser and/or a computer.

Feedback Regulation

The output laser power is regulated in minimum steps of 0.1 W according to a control algorithm programmed into the microprocessor. The feedback thermistor provides input to the algorithm, which uses the temperature history to calculate appropriate changes in output power in order to keep the temperature at the feedback thermistor at a pre-set level. The basic idea of the regulation strategy is to use a high output power in the beginning of the ILT session in order to reach a specified target temperature in a short time. Laser power is then varied in small steps so that the power level corresponds to the power needed to keep a constant temperature at the position of the feedback thermistor. Information on calculated power changes is transferred to the laser, which is set to allow remote operation. Three parameters, "step," "gain," and "ifact," used by the control algorithm, can be altered by the user. "Step" sets a limit to the changes of the output power at each power updating moment, in order to prevent fast oscillations of the output power. "Gain" affects the sensitivity of the algorithm to deviations from the target temperature. "Ifact," finally, determines to what extent the time history of the temperature at the feedback thermistor is to be taken into account.

Phantom Design And Probe Positions

Two cylindrical Plexiglass containers, with inner dimensions 80 mm (diameter) and 65 mm (height) in the single fiber and 110 mm (diameter) and 125 mm (height) in the four-fiber experiments, were used. An 18 mm thick Plexiglass template (25 mm in the four-fiber experiments), with drilled holes for the laser fibers, the thermistor probes, and a light detecting fiber, sealed the top of the cylinder. Positions of the holes are indicated in Figure 2. The phantom used in the four-fiber experiments had two walls, with the interstitium supplied with 37°C water from a circulating water bath (W38-ZA, KEBO AB, Stockholm, Sweden). The phantom used in the single-fiber experiments was immersed into the water bath in order to obtain the same surrounding temperature.

The positioning of the sapphire probes as well as the thermistor probes (Fig. 2) was based on theoretical considerations and on a number of pilot experiments, in which their positions were varied (results not shown). All probes were oriented vertically and parallel to each other. A total of 13 and 14 thermistors (sensors) were used in the single- and four-fiber experiments, respectively, grouped into two five-sensor probes and three or four single-sensor probes. The tip of the sapphire probe was positioned at a depth of 36 mm from the surface in the single-fiber experiments, whereas the tips of the sapphire probes were placed at a depth of 60 mm in the four-fiber experiments.

Experimental Protocol

The ground bovine muscle was heated to 37°C in a plastic bag under running water prior to filling the phantom. Laser fibers, thermistor probes, and the light measuring fiber were inserted to proper positions and the phantom was immersed into, alternatively connected to, the water bath. A steel cannula (outer diameter: 0.8 mm) was preinserted and withdrawn to provide tracks

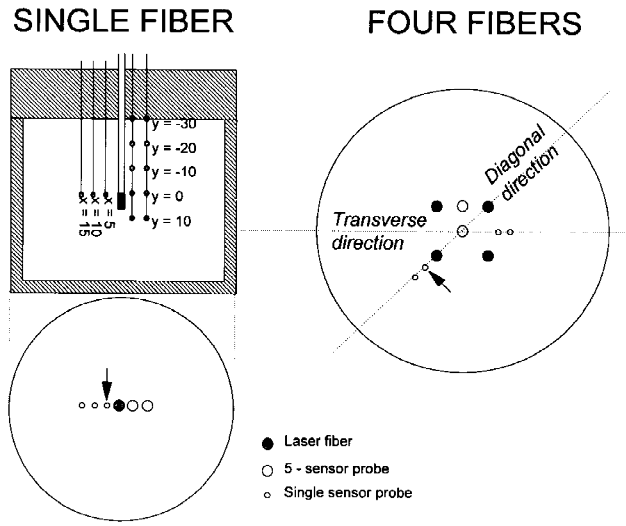

Fig. 2. Positions of the sapphire probe and the thermistors in the single-fiber experiments are shown in the left part of the figure, and the template used in the four-fiber experiments is shown in the right part of the figure. Arrows indicate the positions of the feedback thermistor. Radial and vertical distances are denoted × and y, respectively. All thermistors belonging to a single sensor probe and the thermistors at y = 0 lay in the same plane orthogonal to the upper boundary of the diffusing region of the sapphire probes. The single-sensor probes were positioned at radial distances of 5, 10, and 15 mm from the sapphire probe in the single-fiber experiments, and at 5 and 10 mm distances from both one sapphire probe and the middle of one side of the square formed by the sapphire probes in the four-fiber experiments. The five-sensor probes were positioned at radial distances of 5 and 10 mm from the sapphire probe in the single-fiber experiments and at 0 and 10 mm radial distances from the center of the square in the four-fiber experiments. In the four-fiber experiments the relative vertical positions were identical to those in the single-fiber experiments. The tip of the sapphire probe was positioned at a distance of 36 and 60 mm from the upper tissue boundary in the single- and four-fiber experiments, respectively. The diagonal and transverse directions used in Figure 7 are indicated by two lines.

for the laser fibers in order to ease correct placement. Maximum laser output power was set to 3 W/fiber. New laser fibers, with at least 80% transmission, were always used. After correction for fiber transmission losses, deposited power was 2.4 W in the single-fiber experiments and 1.8 W/fiber in the four-fiber experiments, neglecting the slightly unevenly distributed light among the fibers.

The irradiation session was preceded by 5 min registration of baseline temperatures. Laser thermotherapy was then performed for 40 min. When the irradiation was stopped, temperatures were monitored for 10 min. Temperatures were registered every 5 s. Total energy output from the laser was registered after each experiment. Finally, the filling material was removed from the phantom and the sapphire probe sites were checked for carbonization by visual inspection. Eight single-fiber experiments and twelve four-fiber experiments were performed.

Regulation was defined to begin as soon as the laser power started to decrease. The temperatures during the last minute of the laser regulation period (“end of regulation”), i.e., after 39 min of laser irradiation, were analyzed. Values from the same thermistor positions were averaged for all single-fiber ($n = 8$) and four-fiber ($n = 12$) experiments, respectively. The temperature data from the feedback thermistor were used to calculate the time to reach the regulation temperature in each experiment and to obtain the minimum and maximum temperatures during regulation.

Mathematical Model

Calculating the temperature rise of laser irradiated tissue requires both the light absorption distribution and the subsequent heat transfer process to be modeled. Laser light distribution in tissue was calculated by using the Monte Carlo method [12], which implies the trace of a great number of single photons in the tissue, resulting in the distribution of absorbed photons. For the Monte Carlo simulations, a modified version of a public domain computer program was used [13]. The resulting temperature rise was then calculated by solving the bioheat equation numerically using the method of finite differences [14,15]. The numerical results were compared to the experimentally measured mean temperatures.

Model input parameters consisted of the optical properties of tissue. These were the absorption coefficient, μ_a, the scattering coefficient, μ_s, and the anisotropy factor, g, assuming a Henyey-Greenstein distribution of the scattered photons. Since optical properties at 805 nm have not been reported for bovine muscle, the optical properties of coagulated bovine liver, measured at 850 nm, were used [16]. The values of the optical properties employed in the model were $\mu_a = 0.17\ \text{mm}^{-1}$, $\mu_s = 48\ \text{mm}^{-1}$, and $g = 0.91$ (dimensionless). The thermophysical properties of tissue needed to describe the heat propagation, i.e., tissue density, ρ, thermal conductivity, λ, and specific heat, c, were calculated from relations based on the mass water content of tissue [17,18], which was assumed to be 70%. Values of the input thermophysical parameters were calculated to be $\rho = 1.1 \times 10^3\ \text{kg m}^{-3}$, $\lambda = 0.45\ \text{W m}^{-1}\ \text{K}^{-1}$ and $c = 3.4\ \text{kJ kg}^{-1}$.

TABLE 1. Average Temperatures (±1 SD) at the End of the Regulation Period for Single-Fiber Experiments[a]

Five-sensor probes			Single-sensor probes	
Vertical distance (mm)	Radial distance (mm) 5	Radial distance (mm) 10	Radial distance (mm)	Vertical distance (mm) 0
	Temperature (°C)			Temperature (°C)
−30	38.3 ± 3.4	36.1 ± 2.5	5	49.7 ± 0.17[b]
−20	44.0 ± 4.0	39.7 ± 2.8	10	43.9 ± 0.62
−10	46.9 ± 2.5	42.0 ± 2.3	15	40.6 ± 0.59
0	48.5 ± 1.9	43.2 ± 1.7		
10	45.0 ± 2.5	41.7 ± 1.0		

[a]Vertical distance is zero at the upper boundary of the diffusing section of the sapphire tip. Sites above and below this level are denoted − and +, respectively. Radial distance is zero on the axis of the sapphire tip.
[b]Temperature at the master thermistor.

When calculating the temperature rise resulting from irradiation using a single fiber, a cylindrical geometry was used. The optical fiber and sapphire probe were modeled as a 2 mm diameter cylinder, emitting diffuse light from the distal 5 mm. In the simulations with four fibers, cubic control elements were used, resulting in a cubic calculation domain. Owing to the used geometry, the probe was in this case modeled as a 5 mm line source. The temperature near the line source should therefore be regarded with caution. In the model, the four fibers were positioned in the corners of a square with a side length of 20 mm.

Because 33% of the light that leaves the optical fiber was absorbed in the metal connector between the fiber and the sapphire probe, this absorption had to be taken into account. In the model, the light was assumed to be absorbed in a 4 mm long tissue segment just outside the probe located 19–23 mm above the tip of the sapphire probe, corresponding to the actual position of the metal connector.

The initial tissue temperature was assumed to be 37°C. The initial laser power was chosen to be 1.5 W per fiber. After the temperature reached 50°C at a distance of 5 mm perpendicularly from the probe and 5 mm proximal to the tip of the probe, i.e., at the location of the master thermistor, the laser power was regulated in an on/off manner to maintain the 50°C temperature. Since the timestep used in the simulations was less than 0.2 s, this regulation caused negligible fluctuations in target temperature. The average laser power during the last minute was calculated and compared with the laser power used at the end of the experiment. This time interval was chosen because we wanted to compare simulated and measured temperatures as accurately as possible. In the single-fiber simulations, the calculation domain consisted of an 8 cm high cylinder with a radius of 4 cm. The cubic calculation domain used in the simulation of the experiments with four-fibers had a side length of 8 cm. The spatial resolution was 0.5 mm. The boundaries were assumed insulated in all cases.

Simulating a 40 min laser treatment with a single fiber took approximately 5 min on a DECpc XP 150 (Digital Equipment Corporation, Maynard, MA). The temperature distribution after 40 min of irradiation using four fibers took approximately 8 h to calculate.

RESULTS

Temperatures (mean ± standard deviation, SD) at each thermistor position are shown in Tables 1 and 2, with values corresponding to the end of the regulation period. The mean values for the feedback thermistor were close to the target temperature (50°C) with small standard deviations both in the single- and four-fiber experiments (± 0.17°C and ± 0.06°C, respectively). Standard deviations at all other thermistor positions were larger, ranging from ± 0.6°C to ± 4.0°C in the single-fiber experiments and from ± 0.9°C to ± 5.3°C in the four-fiber experiments. The time elapsed from start of irradiation and until regulation was initiated, which occurred when the temperature at the feedback thermistor was within a few tenths of a degree C from the target temperature, varied substantially between different experiments. In the single-fiber experiments that time was 2.9 ± 1.1 min and in the four-fiber experiments 5.7 ± 3.6 min (mean ± 1 SD) with the maximum times being 4.9 and 12.7 min. Total energy deposited into the tissue ranged from 2.2 to

TABLE 2. Average Temperatures (±1 SD) at the End of the Regulation Period for Four-Fiber Experiments[a]

Five-sensor probes			Single-sensor probes	
Vertical distance (mm)	Radial distance (mm)		Radial distance (mm)	Vertical distance (mm)
	5	10		0
	Temperature (°C)			Temperature (°C)
−30	41.6 ± 4.2	42.5 ± 4.6	19 (diag.)	49.8 ± 0.06[b]
−20	46.0 ± 5.1	46.9 ± 5.3	24 (diag.)	45.0 ± 0.91
−10	48.9 ± 3.4	48.9 ± 3.6	15 (transv.)	47.2 ± 1.8
0	50.1 ± 1.9	49.7 ± 2.0	20 (transv.)	44.4 ± 1.7
10	48.9 ± 4.6	47.8 ± 4.1		

[a]Vertical distance is zero at the upper boundary of the diffusing section of the sapphire tip. Sites above and below this level are denoted − and +, respectively. Radial distance is zero on the central axis of the square formed by the sapphire tips.
[b]Temperature at the master thermistor.

3.4 kJ in the single-fiber experiments and from 6.1 to 12 kJ in the four-fiber experiments. The average deposited power at the end of the irradiation period was 1.0 W in the single-fiber experiments and 0.59 W/fiber in the four-fiber experiments. Carbonization was not observed in any experiment.

Temperature regulation worked well in all experiments, and the temperature variation at the feedback thermistor did not exceed 2.8°C during the regulation period in a single experiment. The minimum and maximum temperatures registered during regulation, in all experiments, were 47.8°C and 51.1°C in the single-fiber experiments and 49.4°C and 52.5°C in the four-fiber experiments, respectively. The largest deviations from the target temperature occurred during the first minutes of the regulation period and always when the time to reach the regulation temperature was relatively short, which resulted in an initial overshoot of the temperature at the feedback thermistor. In the single-fiber experiments the overshoot caused a few oscillations of the temperature at the feedback thermistor, which was not observed in the four-fiber experiments. The temperature at the feedback thermistor and the corresponding output power during one single-fiber experiment and one four-fiber experiment are shown as a function of time in Figure 3a,b.

In the single-fiber experiments, the calculated temperatures radially from the top of the diffusing part of the sapphire probe showed very good agreement with experimental measurements (Fig. 4). Vertically, the correspondence between measured and calculated temperatures was good, as shown in Figure 5. Only the temperatures measured with the four most deeply lying thermistors are plotted in Figure 5, because the most superficial thermistor was located at the upper tissue boundary where the initial temperature was significantly lower than in the tissue center. The complete calculated temperature distribution is shown in Figure 6, illustrating the significant influence of the light absorbed in the connector between the optical fiber and the sapphire probe. At the end of the irradiation period an average laser power of 0.72 W was used in the simulations. The tissue volumes raised to hyperthermic (>45°) and coagulation (>55°) temperatures were found to be 4.2 cm^3 and 0.44 cm^3, respectively.

In the four-fiber experiments, the calculated temperatures in a plane perpendicular to the fiber axes, traversing the top of the diffusing part of the sapphire probes (that is, 5 mm proximal to the tip of the probe), corresponded well with measured temperatures (Fig. 7). The calculated temperatures and the temperatures measured on two vertical lines, one in the center of the square formed by the fibers and one between two fibers are shown in Figure 8. The calculated temperature distributions in the plane perpendicular to the fiber axes at different depths are shown in Figure 9. The top of the diffuser was set to the zero-level. The average laser power emitted from each of the four fibers was 0.65 W at the end of the irradiation period. By using four fibers, the tissue volumes raised to hyperthermic (>45°C) and coagulation (>55°C) temperatures were found to be 44 cm^3 and 2.7 cm^3, respectively.

DISCUSSION

Interstitial laser thermotherapy is a promising method for treatment of localized tumors in the liver and other solid organs. Most previous

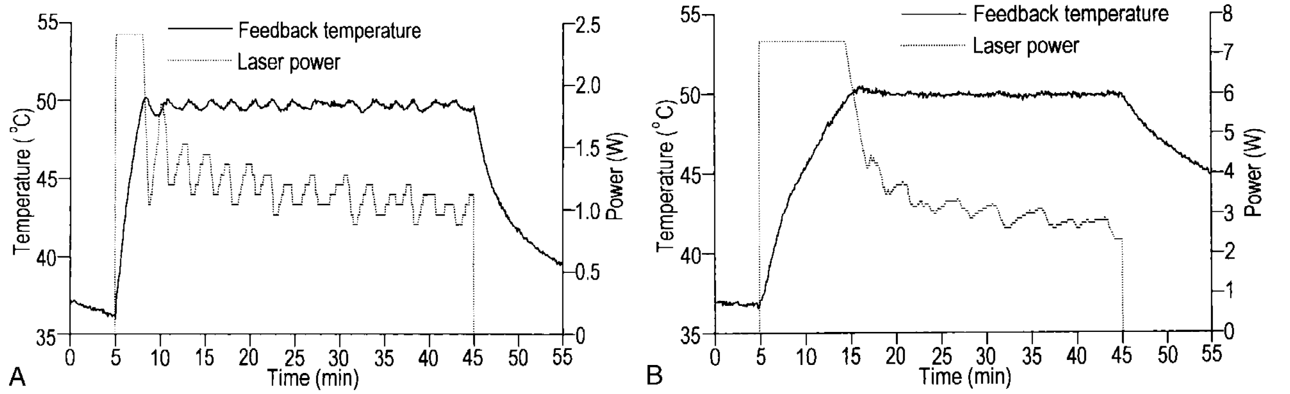

Fig. 3. The temperature at the feedback thermistor as well as total deposited power during **a)** a single-fiber and **b)** a four-fiber experiment. The regulation is slightly less precise in the single-fiber experiment. It can also be seen that the pre-thermotherapy temperature is decreasing in the single-fiber experiment.

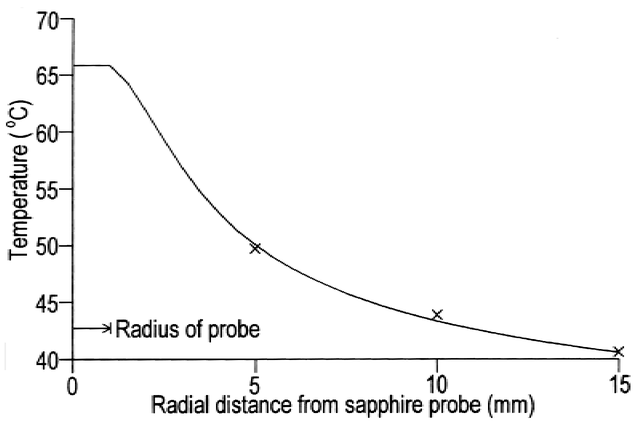

Fig. 4. Single fiber. Calculated (line) and measured temperatures radially out from the top of the diffusing portion of the sapphire probe. In the model, the laser power was regulated to result in a temperature of 50°C at a distance of 5 mm from the probe.

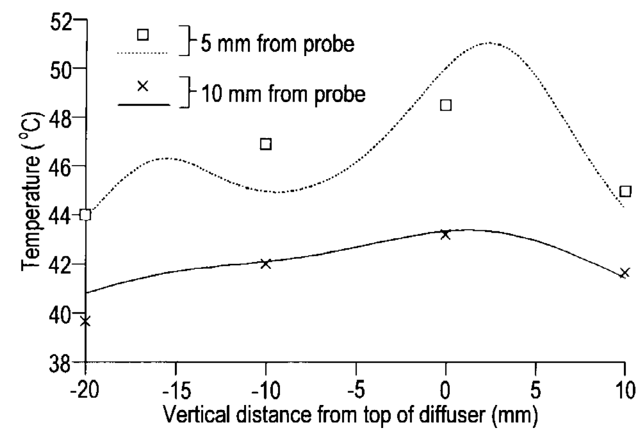

Fig. 5. Single fiber. Vertical calculated (lines) and measured temperatures at a horizontal distance of 5 and 10 mm from the sapphire probe.

investigators have used an Nd:YAG laser, usually in combination with a bare fiber and only rarely together with a multi-fiber system [19,20]. A few have used a feedback regulation system, in which the laser is switched on or off at a predetermined temperature level [5,6,20]. Some have used a diffusing tip giving emission through a larger surface and a reduced risk of carbonization [21,22]. It has been shown that it is important to avoid carbonization in order to obtain a stable temperature regulation [6].

We evaluated a diode laser in combination with a new thermoregulation and thermometry system. Like the laser, the thermoregulation system is small and portable, which makes the entire ILT system convenient to use.

Temperatures in the central parts of the phantoms, before irradiation, varied moderately between the experiments. In the upper part of the phantoms, however, there was cooling by the surrounding air since the phantom could not be completely immersed into the water bath. As a consequence, initial temperatures in that part were relatively low and showed relatively large variation between experiments, which resulted in large temperature variations close to the surface, even at the end of the regulation period. Despite these variations, the evaluation of the operating characteristics is not irrelevant since a similar temperature distribution is present in many situations in vivo. The lower temperatures in the vicinity of the upper tissue boundary, most prominent in the single-fiber experiments, may explain why the power used in the mathematical model was lower than the power used in the experiments.

The present ILT system was capable of

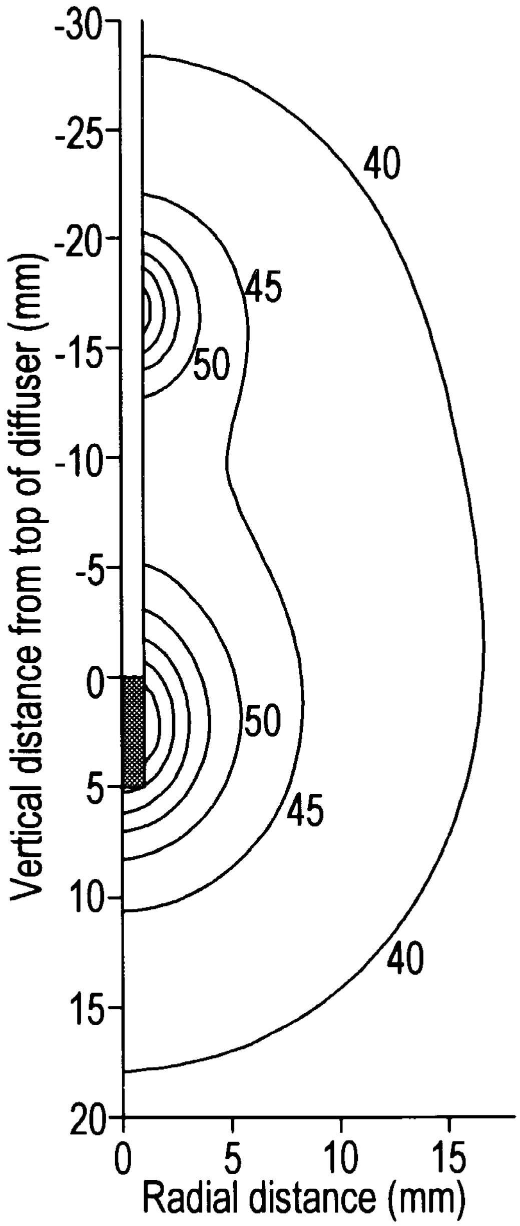

Fig. 6. Single fiber. Calculated temperatures after 40 min of laser heating. Because the temperatures are cylindrically symmetric, only half of the distribution is shown. The isotherms are plotted with 5°C intervals.

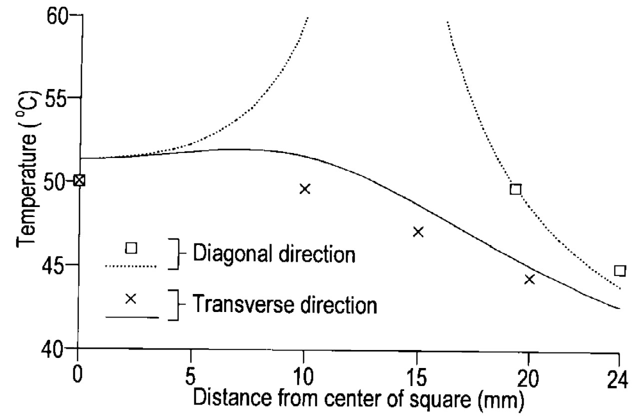

Fig. 7. Four fibers. Calculated (lines) and measured temperatures in a horizontal plane perpendicular to the fiber axes and at the top of the diffusing portion of the sapphire probe. Temperatures above 60°C were omitted. The diagonal direction is defined by a line from the center of the square formed by the four fibers to the corner of the square (where a sapphire probe is located). The transverse direction is defined by a line from the square center to a point midway between two probes (see Fig. 7).

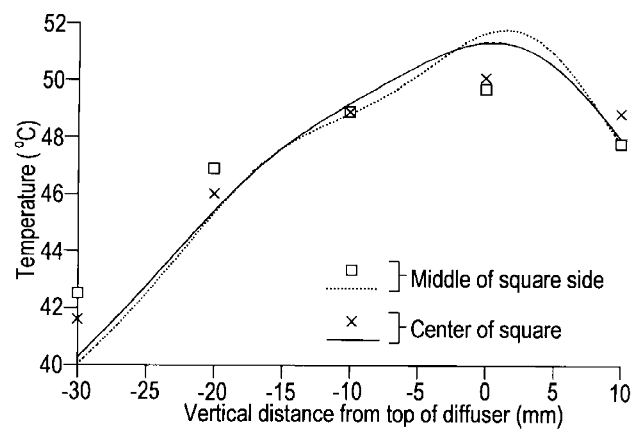

Fig. 8. Four fibers. Vertical calculated (lines) and measured temperatures at the center of the square formed by the four fibers and through the middle of the square side. The top of the diffusing portion of the sapphire probe is assigned a zero vertical distance.

maintaining a reasonably constant temperature at the feedback thermistor, with small variations between experiments (± 0.17°C, 1 SD). Most previous feedback systems have been based on on/off regulation and have performed with similar precision [6,21]. Moderate temperature oscillations were observed when the time to reach target temperature was short but was of limited duration and was confined to a single overshoot in the four-fiber experiments. In the experiments where an overshoot occurred, it may have been caused by positioning the feedback thermistor too close to the sapphire tip, which would result in a faster temperature increase. As the regulation parameters of this system should be optimized for each distance between the feedback thermistor and the laser tip, this uncertainty is of some importance for the performance of the regulation algorithm. We assumed, however, that the regulation parameters chosen were valid for different irradiation geometries in the same medium, if the feedback thermistor was positioned at the same distance

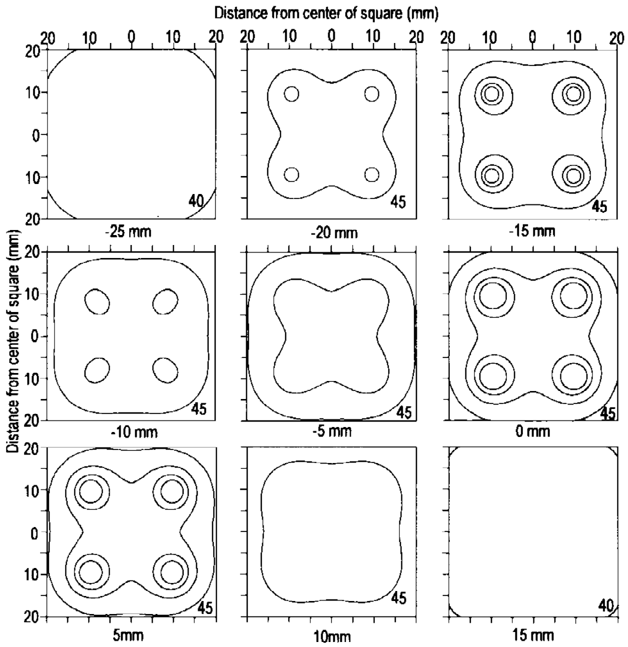

Fig. 9. Four fibers. Calculated temperatures after 40 min of laser heating showing the temperatures in horizontal planes 5 mm apart. The vertical location of the section is shown below each figure, where zero mm indicates the location of the top of the diffusing portion of the sapphire probe. Isotherms are plotted with 5°C intervals. The lowest temperature at each section is shown in the lower right corner of each figure. Temperatures above 60°C were omitted.

from the laser tip. The small difference in regulation characteristics between the single and four-fiber setup supports this assumption and indicates that the system will perform well in clinical situations, where irradiation geometries may vary from one treatment to another. In the clinical situation one may want to place the feedback thermistor at a strategic point, e.g., at a certain distance from the tumor border. As a consequence, the distance between the laser fiber and the thermistor may be more than 5 mm, which makes the regulation process quite complicated due to the time constant of heat conduction [23]. A possible solution is to have inputs to the regulation algorithm from two thermistors, one of which is placed at a strategical point chosen by the clinician, whereas the other is placed close to the surface of the laser probe.

The variation in temperature distribution at the end of the regulation period that was observed between experiments may, like the overshoots, have been caused by misplacement of thermistor probes, in particular of the feedback thermistor. Even a small misplacement may be important due to the relatively steep temperature gradient (1 mm ~ 2–3°C) at 5 mm distance from the laser tip, and will affect the entire temperature distribution. Increasing the distance would result in a smaller temperature gradient at the position of the feedback thermistor. However, this may make the regulation less precise, as observed during pilot experiments performed in order to optimize the regulation parameters (results not shown). Again, the problem might be solved by having inputs from two thermistors to the regulation algorithm.

The fact that no carbonization was observed in our experiments does not prove that the risk of carbonization is reduced by the stepwise power regulation used. However, the functionality of the regulation process ensures smaller, or even negligible, temperature fluctuations close to the sapphire probe surfaces compared to those resulting from an on/off regulation strategy. This might help keeping a temperature close to 100°C at the surface of a light emitting probe without risk of passing that limit. Suitable power levels and corresponding temperature distributions with a specific irradiation geometry may be deduced from numerical calculations.

Davis et al. [24] presented a mathematical model incorporating four point sources and found good agreement with experimental measurements. To our knowledge, the present work is the first to mathematically model the temperature distribution resulting from a multi-fiber interstitial laser treatment employing diffusing light sources. The model uses Monte Carlo simulations to calculate the light absorption distribution, providing source terms in the bio-heat equation. The bioheat equation was then solved numerically using the technique of finite differences. The optical properties used in the model were obtained at 850 nm in coagulated bovine liver. The wavelength used in the present study was 805 nm, and experiments were performed in ground bovine muscle. Although there may be a discrepancy between the optical properties of the tissue used in the experiments and the properties employed in the model, good agreement between calculated and measured temperatures was obtained. The agreement between calculated temperatures and averaged temperature measurements in the region of calculated hyperthermic temperatures (>45°C) was better than 2°C. This indicates that the temperatures at some distance away from the fibers are mainly influenced by heat conduction and not by light absorption, which has been observed previously [25]. Modeling in vivo laser

treatment is complicated by the introduction of blood perfusion. In many cases, such as in treatment of liver tumors, blood inflow can be temporarily occluded [26], making the model results reliable. In this context, it may also be observed that temperature distribution and control is similar when interstitial laser thermotherapy using feedback regulation is performed in processed tissue and in vivo [4,6,26].

It was shown that the laser light absorbed in the metal connector between the optical fiber and the sapphire probe caused a significant contribution to the temperature elevation proximal to the light emitting portion of the probe, creating a pear shaped temperature distribution around the single fiber (Fig. 6). The maximum tissue temperature was, however, found in the region primarily affected by the diffuse laser light.

The results from numerical simulations of four-fibers placed in the corners of a 20 mm square using a laser power of 0.65 W per fiber, showed that an approximate cylinder 3 cm in height and 2 cm in radius was raised to hyperthermic temperatures (>45°C). Using four fibers created a hyperthermic volume 10–11 times greater than that obtained using a single fiber. The coagulation volume (tissue temperature > 55°C) was six times larger after treatment with four fibers as compared to treatment with one fiber. For a certain tumor size, mathematical modeling can be used to gain knowledge of the optimal positioning of multiple laser fibers with respect to the temperature distribution.

It is concluded that the stepwise power regulation system was efficient in maintaining a stable target temperature. The results indicate that the present ILT system together with multiple fibers can produce lesion volumes large enough to treat most tumors in a single session and that computer simulation may be useful for planning the treatment.

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